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SYNOPSIS: Forced-Vibration tests were performed on two large-scale same models constructed on soft and hard ground in order to investigate the effect of the hardness and the stratification of the supporting ground on the vibration characteristics of simulated reactor buildings. The soft ground is almost stratification ground, and the hard ground is almost uniform ground. The test models are RC rigid frame structure with shear walls. In the tests, sinusoidal wave excitation was applied by the excitor. The vibration characteristics of the test models, earth pressure at the bottom of the base mat and the vibration characteristics of the surrounding ground were investigated. In the analysis, the soil impedances, the responses of the structure and the surrounding ground were almost simulated by Axisymmetric Finite Element Method.

INTRODUCTION

As regards dynamic soil-structure interaction problems for the seismic safety, it is important to comprehend the effect of the hardness and the stratification of the supporting ground on the vibration characteristics of a structure.

This paper describes the experimental studies for evaluation of the influence on the vibration characteristics of a structure, the earth pressure at the bottom of the base mat and the vibration characteristics of the surrounding ground because of the difference between hard and soft or stratification and uniformity on the supporting ground. These studies are results of the forced vibration tests of two large-scale models, which were constructed on hard and soft ground taking account of the non-dimensional frequency, relative weights of each part and mode shape of the PWR-type reactor buildings which are to be constructed in Japan, and these tests are parts of a series of large-scale model forced-vibration tests (Izumi et al., 1989, 1990), and the analyses of the test results are carried out.

TEST CONDITION

Description of Soil Properties

Two type supporting grounds were set up. One of them (called the soft ground in this paper) is composed of the weathering-tuff-breccia with the velocity of the transverse waves between 320 ~ 440 m/s (thickness : approximatery 8 meters) and the tuff-breccia under the upper stratum with the velocity of the transverse waves between 920 ~ 1600 m/s. The other (called the hard ground in this paper) is mainly composed of the sandstone with the velocity of the transverse waves approximately 1050 m/s. The former is approximately stratificational ground, the latter is approximately uniform ground. These description of soil properties were confirmed by the boring examination and the PS logging of the supporting and the surrounding ground. The thickness and the velocity of the transverse waves of the surface loose layer (the velocity of the transverse waves was dropped) because of excavating was confirmed by the elastic wave test on surface.

Fig.1 Test Model

Test Models

The test models shown in Fig.1, RC rigid frame structure with shear walls, have a square shaped base with each side measuring 8 meters, and those height are 10 meters, and those weight are approximately 920 ton. The shape of the model is shown in Fig.2. The tests were performed on two models which are the same structures constructed on soft (C1 test) and hard (D1 test) ground mentioned in the former paragraph.

Test Method

In the tests, vibration was applied by the excitor placed on the center of the top floor or the center of the base mat floor. The response amplitude and the phase lag from the vibromotive force were measured at the selected observation points under stationary state at the predetermined frequencies. The items mesured are the displacement in various parts of the models, earth pressure at the bottom of the base mat and acceleration in the surrounding ground.

EXAMINATION OF TEST RESULTS

Vibration Characteristics of Test Models

The natural frequency, the damping factor and the mode ratio at the top of the model at the natural frequency are shown in Table 1. The damping factor of the C1 test for the soft ground is larger than that of the D1 test for the hard ground, and the deformation ratio of the C1 test is smaller than that of the

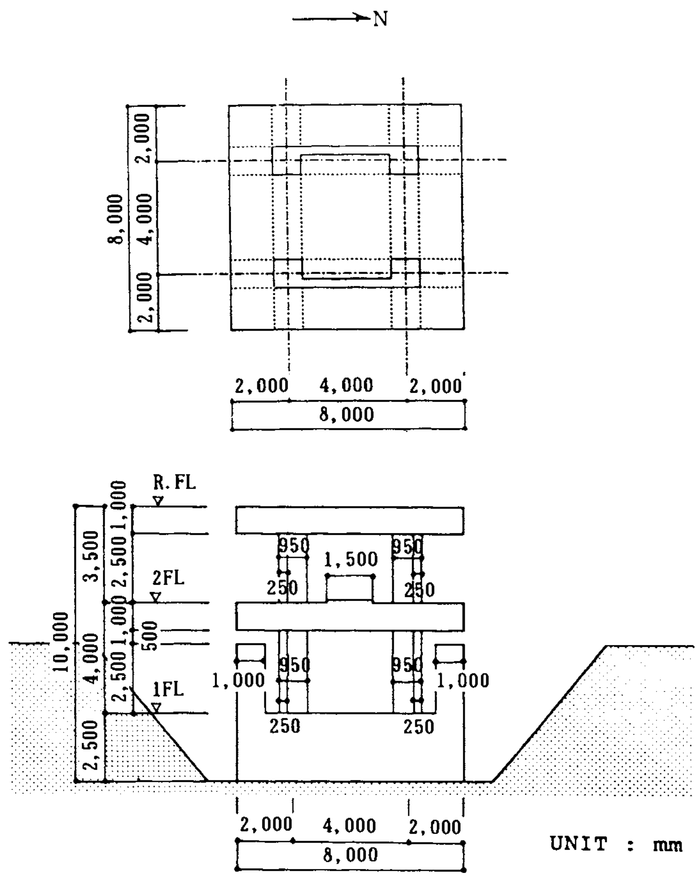
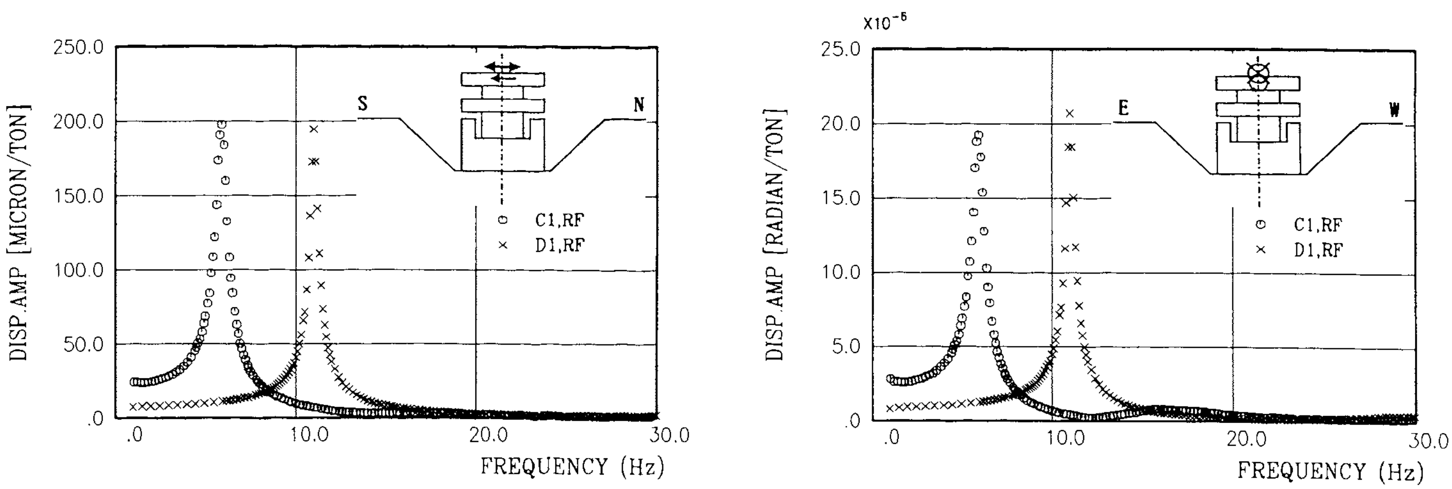


Fig.2 Shape of Model

Table 1 Test Results

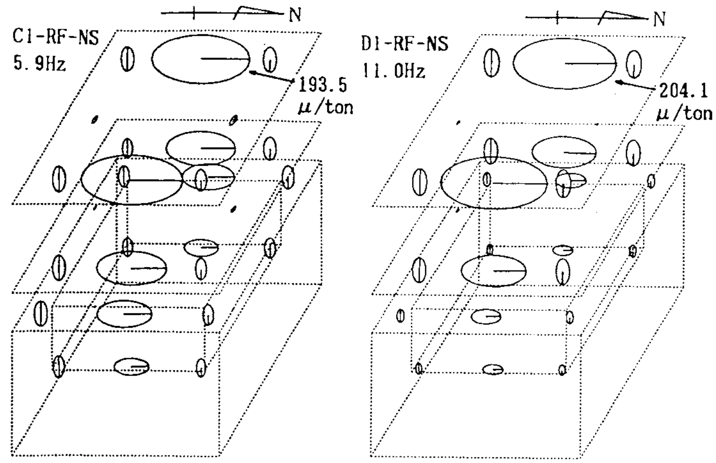
Test	Natural Frequency (Hz)	Damping Factor (%)	Contribution Ratio		
			Swaying (%)	Rocking (%)	Deformation (%)
C1 (Soft Ground)	5.9	5.1	17	74	9
D1 (Hard Ground)	11.0	1.9	9	41	50



(a) Horizontal (b) Rotational

Fig.3 Resonance Curves of Top Floor

D1 test, because of the degree of each ground stiffness. The resonance curves at the center of the top floor determined from the test results are shown in Fig.3 with making a comparison between C1 test and D1 test. The horizontal displacement of the C1 test at the natural frequency are nealy equal to that of the D1 test, but the rotational displacement of the C1 test is smaller than that of the D1 test because of the deformation ratio, and the D1 test results have a sharp peak because of the small damping factor. The vibration modes of the test models at the natural frequency are shown in Fig.4. The rotational displacements of each floor of the C1 test are nealy equal, because of the small deformation ratio.

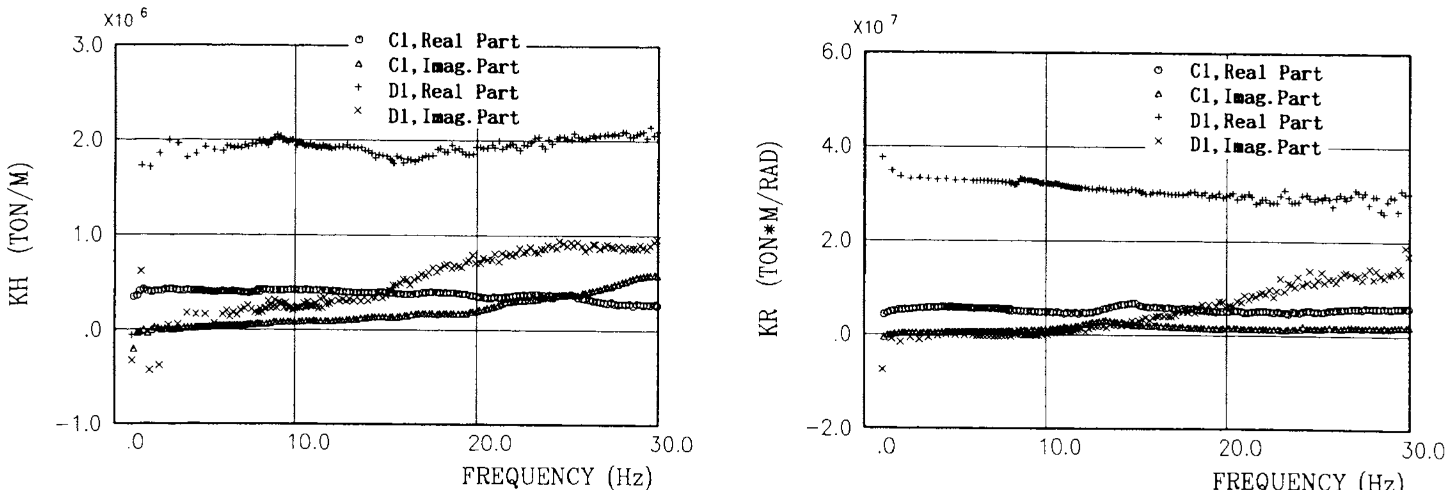


(a) C1 Test (b) D1 Test

Fig.4 Modes of Test Model

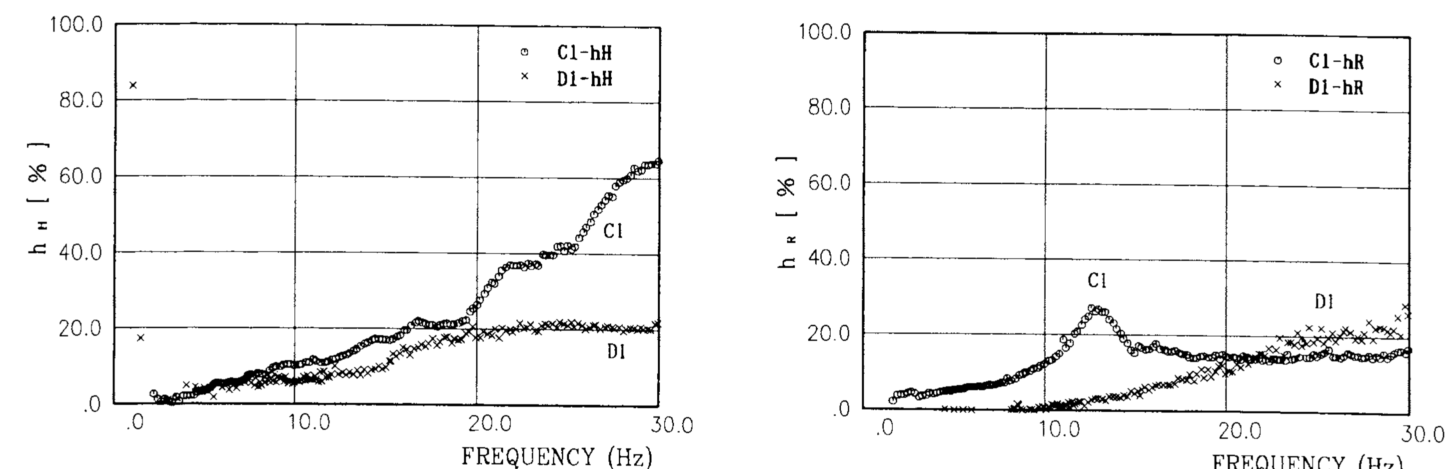
Soil Impedance

The soil impedances (K_H, K_R) calculated from the tests results are shown in Fig.5, and the equivalent damping factors (h_H, h_R) calculated from these soil impedances are shown in Fig.6. The real parts of the soil impedances of the D1 test are approximately five times as large as those of the C1 test, because of the stiffness of the supporting ground. The effect of the radiation damping of the soft ground is larger than that of the hard ground, on the whole, from a comparison of the equivalent damping factors, and this characteristic is conspicuous in higher frequency as regards the horizontal component.



(a) Horizontal (K_H) (b) Rotational (K_R)

Fig.5 Soil Impedances (K_H, K_R) at Base Bottom



(a) Horizontal (h_H) (b) Rotational (h_R)

Fig.6 Equivalent Damping Factors (h = Imag./ (2× Real))

Earth Pressure at Base Bottom

The distributions of the dynamic earth pressure at the bottom of the base mat at the natural frequency are shown in Fig.7. The distributions of the vertical and the horizontal earth pressure are the pseudo rigid-plate distribution, which has small values near the center of the base bottom and large values at the edge of the base mat. The vertical earth pressure of the C1 test is corresponding to the rocking motion of the test model, but as regards D1 test, the south side pressures are larger than the north side pressures.

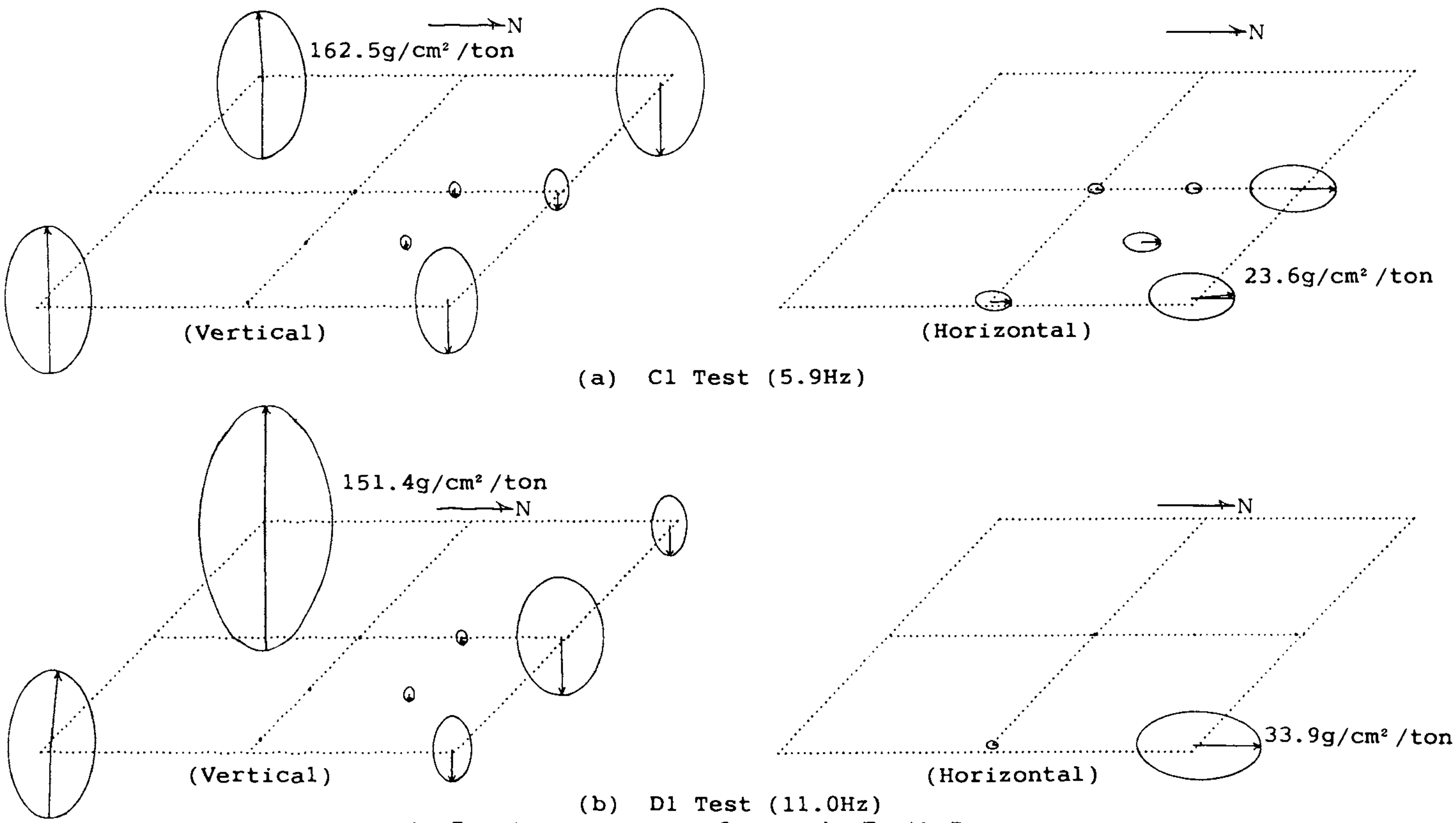


Fig.7 Distributions of Dynamic Earth Pressure

Vibration Characteristics of Surrounding Ground

The comparison of the resonance curves of excitation direction acceleration in surrounding ground is shown in Fig.8. The peak of 5.9 Hz of C1 test and the peak of the 11.0 Hz of the D1 test are

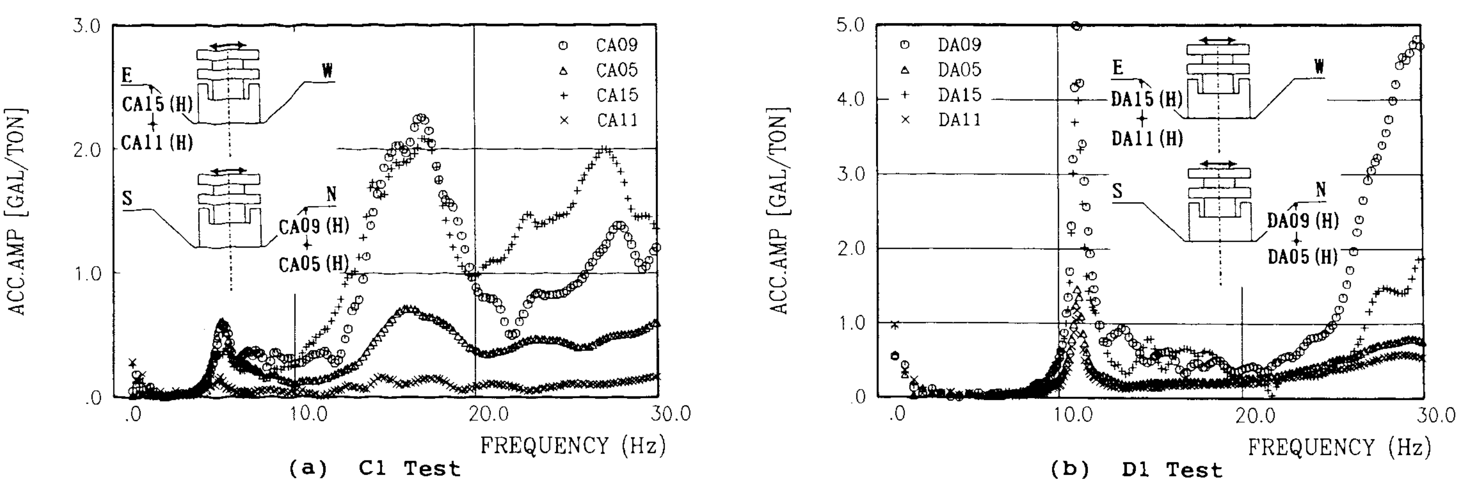
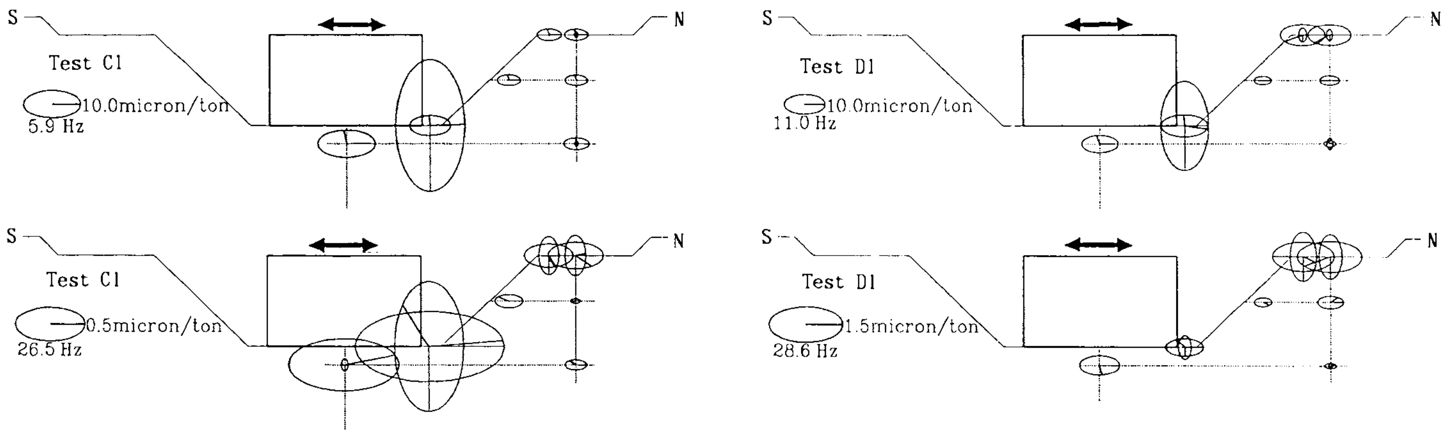


Fig.8 Resonance Curves of Surrounding Ground

the first natural frequency of the soil-structure system. Complex peaks are observed in higher frequency ranges on surface ground as regards Cl test results, these peaks appear because of the stratification of the Cl test supporting ground, and the peak of near 30 Hz of Dl test results is the natural frequency of the slope part of the surrounding ground. The comparison of the surrounding ground mode between near the natural frequency and higher frequency area is shown in Fig.9. Regarding both Cl test and Dl test, in the slope of the surrounding ground, the horizontal response is conspicuous near the natural frequency, but at the higher frequency, the horizontal and vertical response is conspicuous on the surface ground, these things may result from Rayleigh wave occured in the excitation direction of the surround ground.



(a) Cl Test (b) Dl Test

Fig.9 Modes of Surrounding Ground

ANALYSIS

Analysis Method

Analytical technique is Axisymmetric FEM, whose model is shown in Fig.10. In this method, the upper structure was modeled by a lumped mass model, the base mat was modeled by a rigid body and the ground was modeled by axisymmetric finit eiement. The square base was replaced by the equivalent circle, whose area is equal to the square base. The unit weight of reinforced concrete was fixed at 2.4 t/m^3, and the Young's modulus was fixed at 280 kg/cm^2 by the results of compression tests of the concrete, and the shear modulus was fixed at 120 kg/cm^2, and the damping factor of the concrete was fixed at 0.01. The soil constants for analysis are shown in Table 2. Those soil constants were fixed from the results of the boring examination, the PS logging and the elastic wave test on the supporting and the surrounding ground.

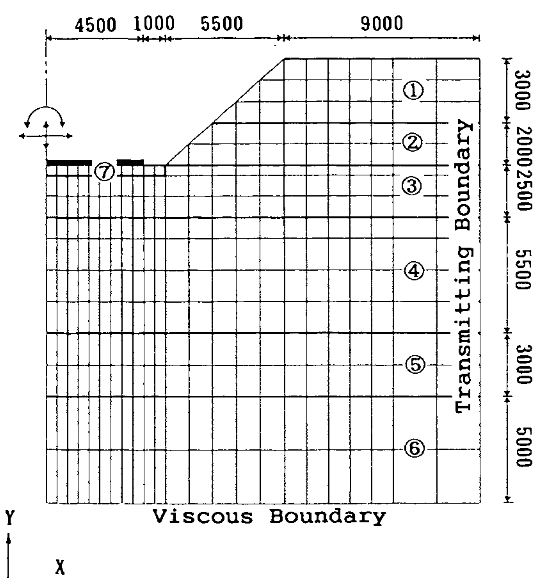


Fig.10 Axisymmetric FEM

Table 2 Soil Constants

	C1				D1			
	ρ (m/s)	Vs (m/s)	ν	h(%)	ρ (m/s)	Vs (m/s)	ν	h(%)
①	1.3	130	0.41	5	1.5	160	0.43	5
②	1.4	280	0.31	5	1.7	350	0.43	2
③	1.7	320	0.29	5	1.9	1050	0.28	2
④	1.7	440	0.46	3	1.9	1050	0.28	2
⑤	2.1	920	0.46	3	1.9	1050	0.28	2
⑥	2.1	1600	0.38	3	1.9	1050	0.36	2
⑦	1.4	250	0.29	5	1.7	400	0.28	2

ρ : density
V_s : velocity of transverse wave
ν : poisson's ratio
h : damping factor

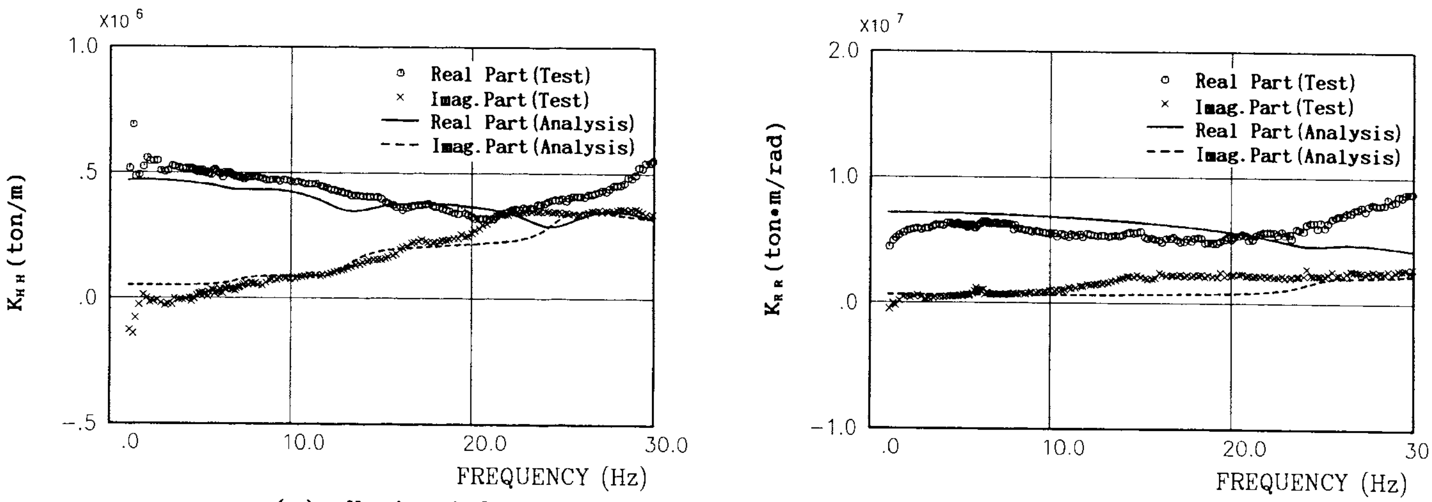
Results of Analysis

The comparison of analytical and test results on soil impedances (K_{HH}, K_{RR}) is shown in Fig.11(a) (C1 test) and Fig.11(b) (D1 test). The soil impedances (K_{HH}, K_{RR}) of test results were calculated from eq.(1) and eq.(2) with using two test results which are different from each other in the excitation point (the top floor, the base mat floor).

$$K_H = K_{HH} + K_{HR} \cdot (\theta_0 / u_0) \tag{1}$$

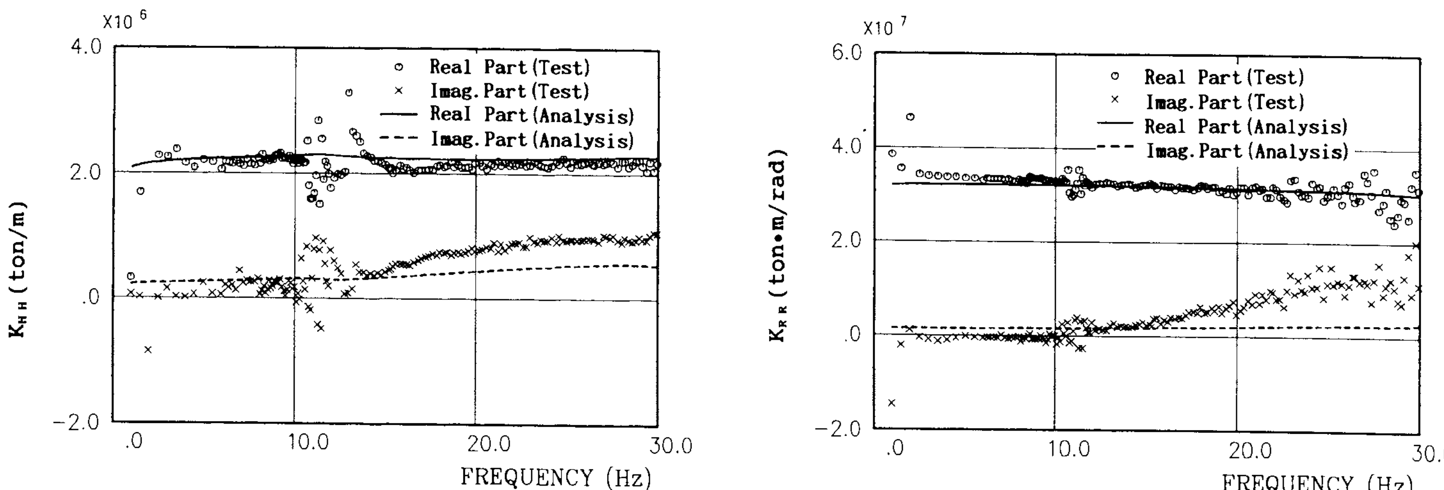
$$K_R = K_{RR} + K_{RH} \cdot (u_0 / \theta_0) \tag{2}$$

In these equations, θ_0/u_0 (Rocking/Sway) is the mode ratio of the base bottom. Regarding both of C1 test and D1 test, the analytical results correspond to the test results. In order to compare the analytical and test results, the resonance and phase lag curves at the center of the base bottom are shown in Fig.12, the resonanse and phase lag curves in the excitation direction determined from acceleration in the supporting ground and underneath the test models are shown in Fig.13, and those for the resonance and phase lag curves of excitation direction acceleration of the surrounding ground are shown in Fig.14. The analytical results correspond well to the test results as regards the response of the structure, and as regards the response of the supporting and surrounding grounds, the amplitude has a little difference, but the tendency of the analytical results correspond almost to the test results.



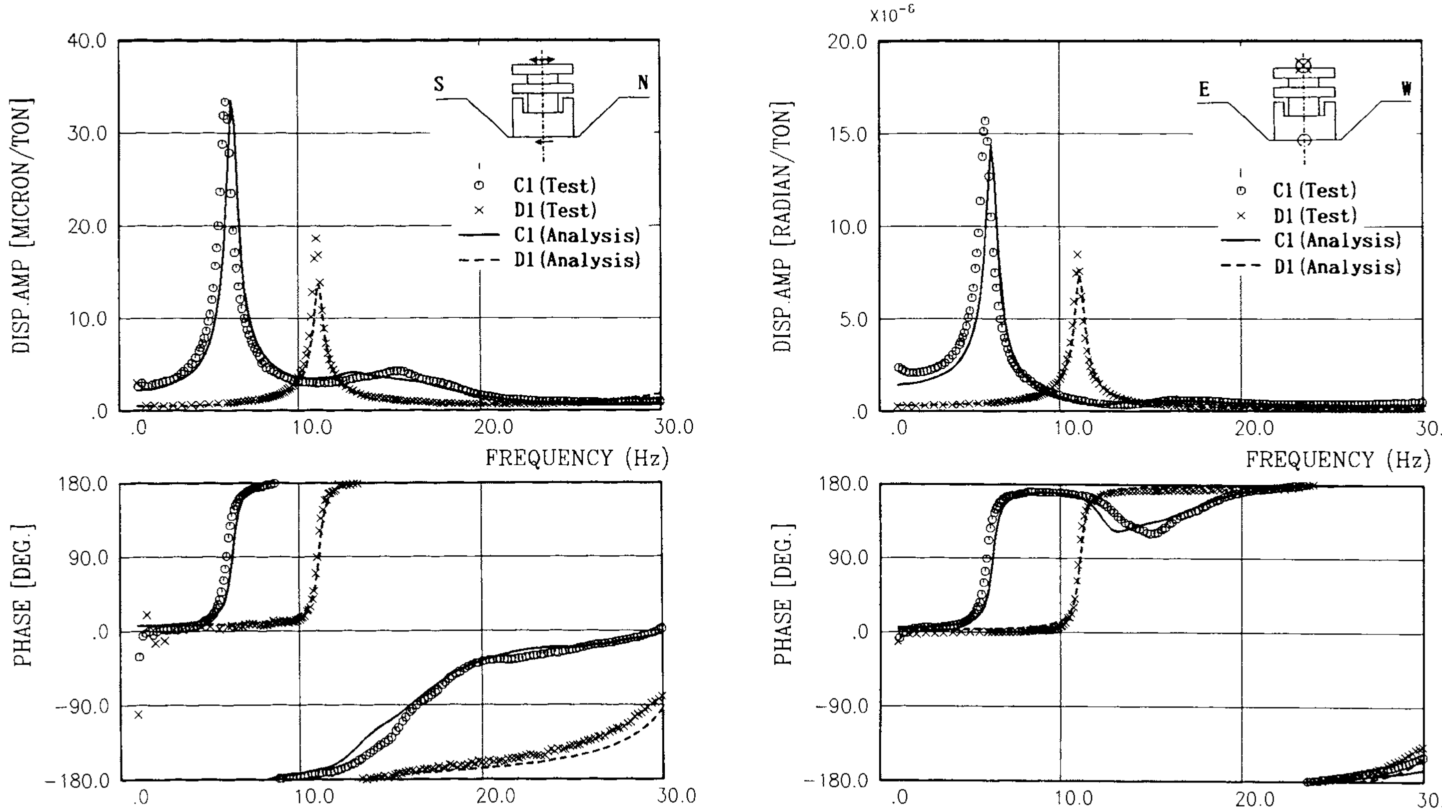
(a) Horizontal (b) Rotational

Fig.11(a) Comparison of Analysis and Test on Soil Impedances (C1 Test)



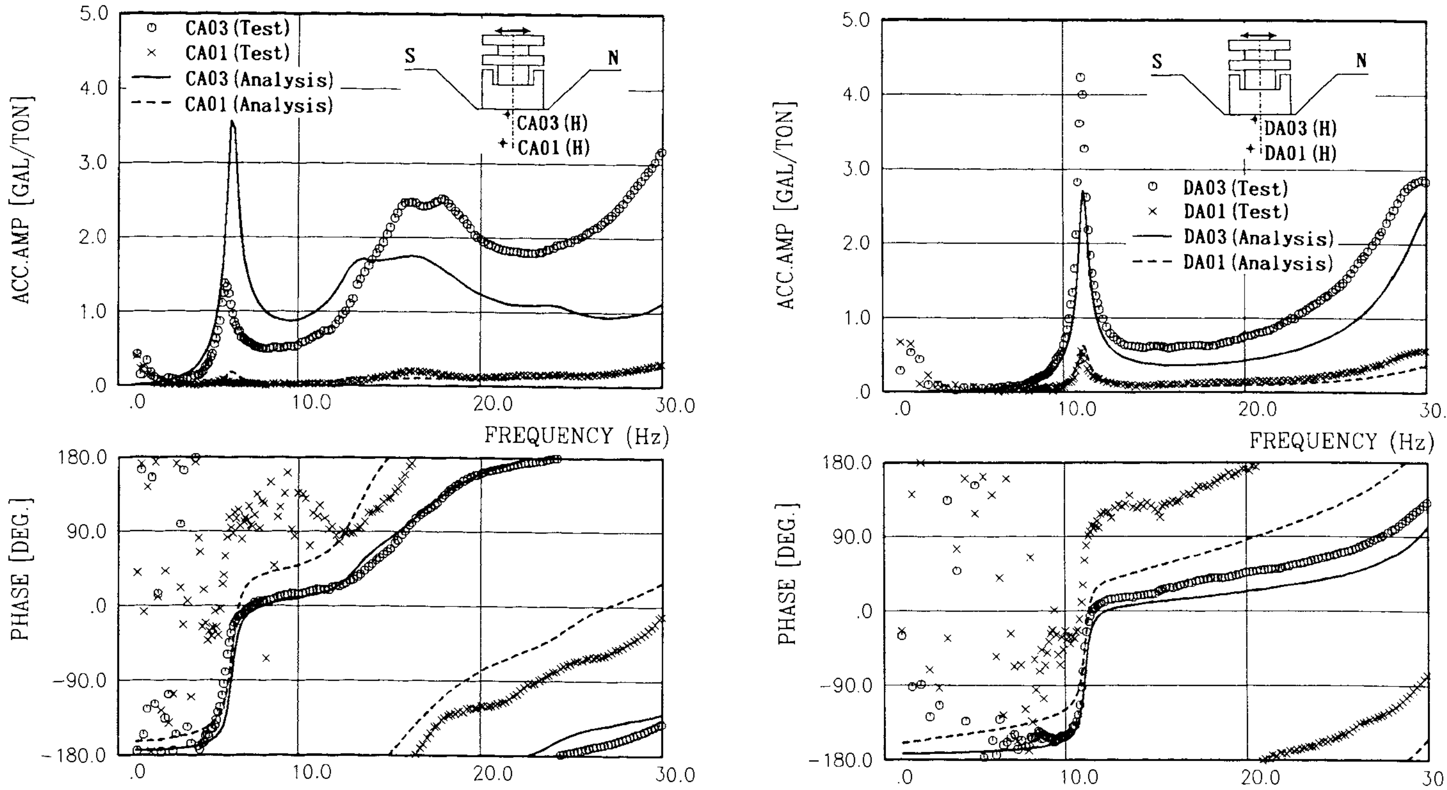
(a) Horizontal (b) Rotational

Fig.11(b) Comparison of Analysis and Test on Soil Impedances (D1 Test)



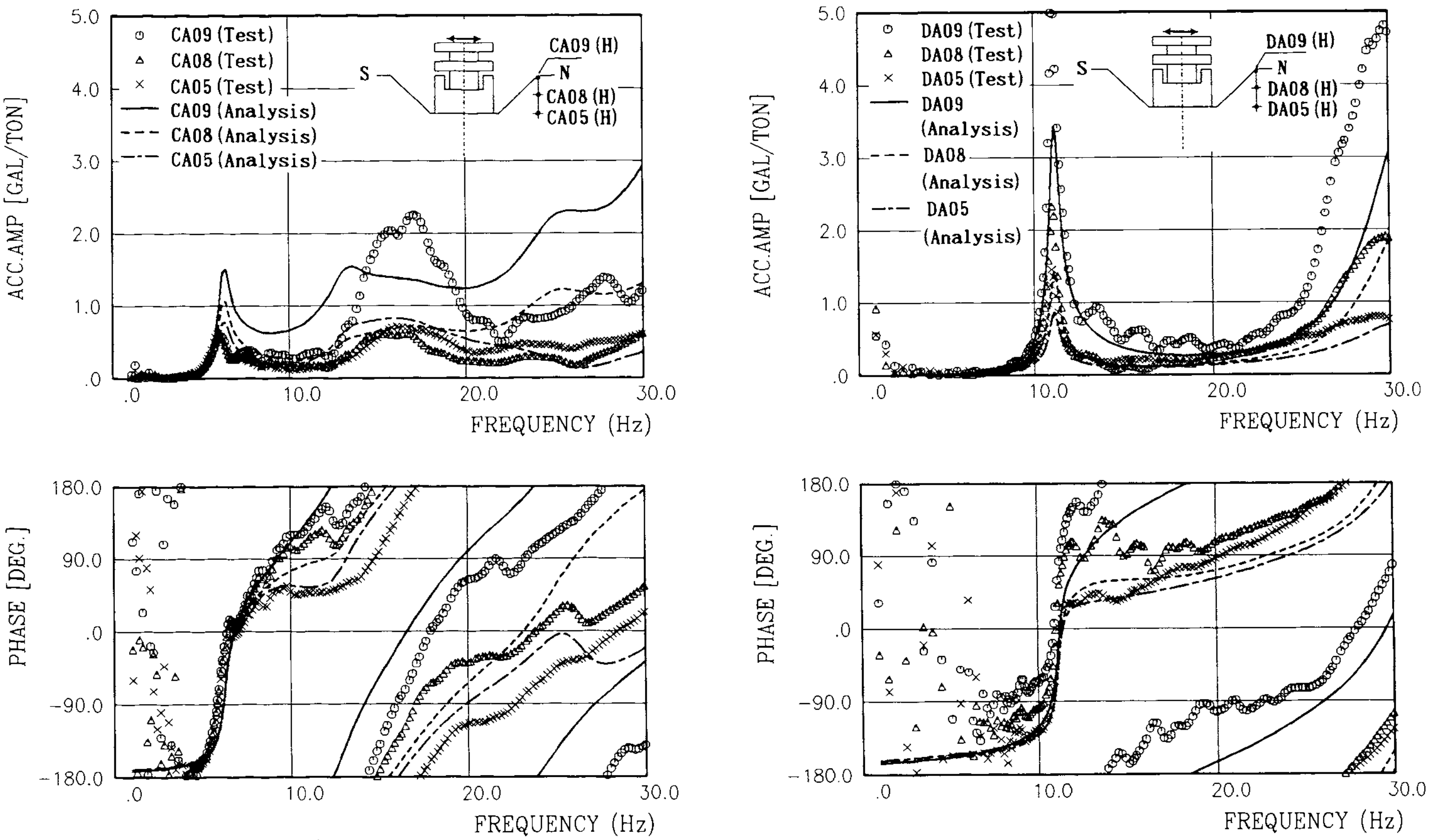
(a) Horizontal (b) Rotational

Fig.12 Comparison of Analysis and Test on Resonance Curves and Phase Lag Curves at Base Bottom



(a) C1 Test (b) D1 Test

Fig.13 Comparison of Analysis and Test on Resonance Curves and Phase Lag Curves of Supporting Ground



(a) C1 Test (b) D1 Test

Fig.14 Comparison of Analysis and Test on Resonance Curves and Phase Lag Curves of Surrounding Ground

CONCLUSIONS

The effects of the hardness and the stratification of the supporting ground on the vibration characteristics of the soil-structure system were investigated from the results of the forced vibration tests of the large-scale models constructed on the field. The following conclusions were drawn. From the results of the tests, the effect of the radiation damping on the soft ground is greater than that on the hard ground except the rotational component at the higher frequency, and as regards the vibration characteristics of the surrounding ground, complex peaks are observed in higher frequency ranges on surface of the soft and stratificational ground. From the analytical studies, not only the soil impedances and the response of the structure but also the characteristics of the response of the surrounding ground can be evaluated with using Axisymmetric Finite Element Method.

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